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Aircraft trajectory planning under uncertainty by light propagation

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Abstract

In the SESAR framework (Single European Sky ATM Research), the need to increase the air traffic capacity motivated the 4D (space + time) aircraft trajectory planning. This paper deals with an important Air Traffic Management (ATM) problem that consists in generating sets of 4D conflict-free trajectories (the *tactical planning* problem). The Light Propagation Algorithm (LPA) was introduced in [1] to deal with this problem. LPA has recently been shown to manage successfully a full day of traffic over the French airspace, removing all conflicts while satisfying ATM constraints.

In this paper, we adapt the LPA to take into account uncertainties in trajectory prediction. We introduce and test a new algorithm called u/LPA (LPA under uncertainty) on the same day of traffic. For some situations, uncertainties reduce so much the search space that the standard algorithm cannot guarantee conflict free situation. As a consequence, one must include some time constraints for few trajectories (so-called *RTA points*: Real Time of Arrival constraints) in order to remove the remaining conflicts. The goal of RTA points is to impose an aircraft to be at a specified position at some given time. This results into a new optimization formulation of the tactical trajectory planning problem involving the decision as to where/when RTA points should be imposed. In order to solve this new problem, here we are content with a simple heuristic that yields encouraging results.

Keywords: Optimization, Air Traffic Management, Conflict Resolution, Uncertainty.

1. INTRODUCTION

During recent years, several methods have been proposed to find an optimal solution that could solve conflicts in air traffic. The aim of these methods is to find for each aircraft, an optimal 4D trajectory that avoids conflicts with other aircraft, reaches the destination point and optimizes a cost function which depends on the travel duration. Several methods have been proposed to address this problem like genetic algorithms [2], Ant colony optimization algorithms [3], navigation-function based approach [4] and mixed integer programming [5]. However, each of these methods provides only a partial solution to the problem. They either do not satisfy all constraints imposed by ATM or they are not guaranteed to reach a feasible (conflict-free) solution in a given computing time.

The objective of the Light Propagation Algorithm (LPA) introduced in [1], based on an optical analogy, is to find for each aircraft a feasible (relevant to ATM constraints) optimal 4D trajectory, avoiding conflicts and which minimizes a criterion based on a local metric. However, LPA does not take into account the

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uncertainties present in ATM. In this paper we present an adapted version of LPA and call this new algorithm, that takes into account such uncertainties, u/LPA (LPA under uncertainty) .

In the next section, we summarize the LPA approach. In section 3, we present the uncertainty model we use, we then introduce the new algorithm u/LPA adapted from LPA to deal with uncertainty. In section 4, we introduce a new optimization formulation of the conflict resolution problem under uncertainty when considering the use of RTA points. Then, we detail the different steps of the methodology we use to solve this new problem. Finally, we present in section 5 encouraging results obtained with our methodology on a half day of traffic over the French airspace.

2. LIGHT PROPAGATION ALGORITHM

The *Light Propagation Algorithm* (LPA) introduced in [1] computes smooth approximate geodesic trajectories able to avoid static or dynamic obstacles. This algorithm mimics light propagation between a departure point towards an arrival point in an environment where obstacles are modeled by high refractive-index areas. By controlling the index landscape, it is possible to ensure that the computed trajectories meet ATM speed constraints and to guarantee that aircraft remain at specified minimum distance from obstacles.

We consider an optimization problem whose objective function gives as output a positive real value for any smooth curve of $\mathbb{R}^3 \times \mathbb{R}^+$ (space + time). This value is computed by integrating a local metric along the curve. One can thus represent length, travel time or the cost associated with a trajectory by a suitable choice of local metric. Determining an optimal trajectory will therefore reduce to search a shortest-length (with regards to the chosen local metric) geodesic between two points of $\mathbb{R}^3 \times \mathbb{R}^+$.

LPA seeks to find numerically the path followed by light between two points in 4D space which is provided with a refractive-index map. For this, one introduces a light source at the departure point. Then, light propagation is simulated from this source using the wave propagation theory of light proposed by Christiaan Huygens. LPA is therefore a wavefront propagation algorithm in 4D. The wavefront is discretized in space: several light beams are launched in various directions from the source. The wavefront is propagated in time dimension using a time step dt. The path of the first ray that reaches the arrival point corresponds to an approximation of a geodesic. LPA is implemented within a *branch-and-bound algorithm* (B&B) [6]. Branching is defined so as to simulate the wavefront propagation. More precisely, light beams are thrown in straight lines from the current node in all directions in the half space toward the destination point, with a given discretization angle step $d\theta$. LPA maintain aircraft vertical profile so that there is no discretization in the vertical plane. A beam propagates in one direction with a velocity that depends on the refractive indices of the media through which it passes, reaching a son node of the current node after the time step dt.

The algorithmic parameters $d\theta$ and dt are set by the user. The user of LPA must moreover set a distance-from-destination tolerance $\epsilon > 0$. LPA relies on a procedure "*LaunchRays(N)*" (for a node N) for the branching process of the B&B algorithm:

Procedure LaunchRays(N)

i. Discretize the half-space between node N and the arrival point with time step dt and angle step $d\theta$.

ii. Determine new child nodes and their approximate lower bounds using the following rule:

For any light beam, if it goes into a region with index I, its velocity v inside this region is $v = \frac{v_{max}}{I}$, where v_{max} is the maximum speed of the aircraft.

For any child node, compute its approximate lower bound as described in [1].

iii. Remove node N from the tree and add its children.

The main steps of LPA are as follows (D and A are respectively the trajectory departure and the arrival points):

1. Set TrajSolution := $\emptyset$. Set upperBound := $+\infty$.

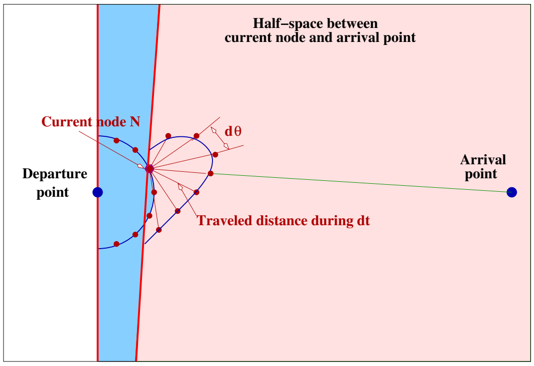

Fig. 1. Launching rays from current node N in 2D+time.

2. *LaunchRays(D).*

3. While there are still unexplored nodes in the tree, choose a node N then:

If distance$(N, A) \leq \epsilon$ and approximate lower bound of node $N \leq$ upperBound then:

- TrajSolution:= Set of ascendant points of N.

- upperBound:= approximate lower bound of N.

- remove from the tree all nodes whose approximate lower bounds are greater than upperBound.

Else

LaunchRays(N) (see Figure 1).

In order to deal with the conflict resolution problem, LPA controls sequentially several aircraft trajectories by selecting aircraft according to some priority rule chosen by the user (by default aircraft are selected according to their lexicographic order). The first aircraft behaves as if there where no other aircraft in the airspace. The second aircraft considers the first aircraft's trajectory as a constraint and must maintain the standard separation from it. At the m^{th} step, LPA synthesizes a trajectory for the m^{th} aircraft in $\mathbb{R}^3 \times \mathbb{R}^+$ space that must avoid the 4D tubes representing the dynamic protection zones of the $m-1$ previous aircraft (already computed). The section of such a 4D tube at time t is an aircraft protection zone (in $\mathbb{R}^3$). It is a cylinder whose basis is a disk of radius equal to the minimal separation distance between two aircraft in the horizontal dimension (5 Nm) and whose height is twice the minimal separation distance in the vertical dimension (2000 ft). To guarantee conflict-free aircraft trajectories, LPA directly eliminates any beam that enters such a 4D tube within the B&B process.

The refractive index function that LPA uses guarantees avoidance with the other aircraft 4D tubes. The index function, I, is set to a sufficiently high constant value (I_{max}) inside these tubes and it is set to the value 1 elsewhere .

Real world problem

LPA was tested in [1] on a real-world conflict resolution problem: a real day of traffic over the French airspace simulated using historical flight plans for August 12, 2008 and a traffic simulator (see Figure 2(a)). Each trajectory is a list of points sampled every 15 seconds. The goal is to find for every aircraft a conflict-free trajectory (a trajectory that does not enter the protection zone of another aircraft) connecting its departure point to its arrival point.

The problem instance was built by an iterative process using moving time windows of 21 minutes. For each time window, the relevant trajectory segments were extracted from the complete trajectory set (see Figure 2(b)). Then, conflicts were detected and trajectory segments which are in conflict were gathered together and called *conflict clusters* (see Figure 3(a)).

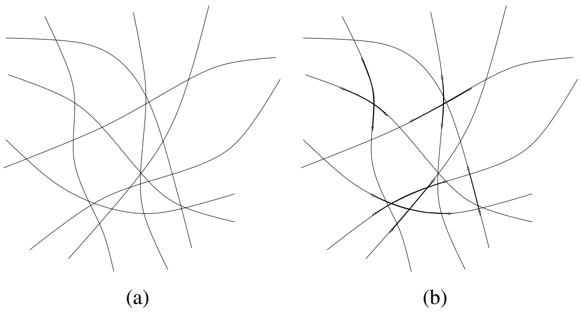

Fig. 2. A complete trajectory set (a) and trajectory segments relevant to a given time window (in bold) (b).

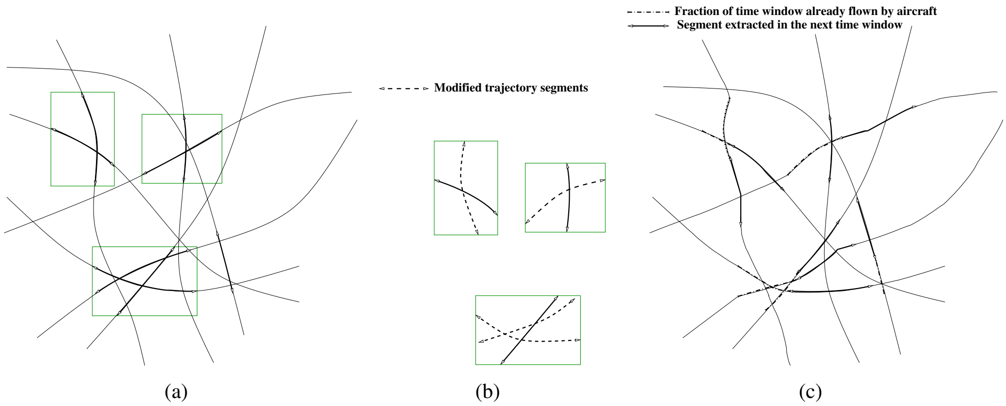

Fig. 3. Conflict detection (a), conflict resolution (b) and next iteration (c).

In the numerical results reported in [1], all clusters were treated separately by the LPA in order to produce conflict-free trajectories (see Figure 3(b)). The old trajectory segments are then replaced by the solutions produced by LPA. Then, aircraft are "allowed" to fly for a period corresponding to a given fraction of the time window (one third, in [1]) during which aircraft follow the new trajectories. This process is repeated for the next time window (see Figure 3(c)).

The results produced on this day of traffic involved about 8000 flights and the initial trajectories (before conflict resolution) induced a total number of clusters equal to 3344. LPA nearly solved all conflicts, with only 28 situations for which conflict-free trajectories were not found (situations corresponding to some aircraft being already in conflict at the beginning of the simulation, for instance at their departure point). Only 1501 trajectories were modified by LPA to reach such a conflict-free planning.

3. UNCERTAINTIES

In the real-world problem, LPA requires extracting trajectory segments present in each time window in order to predict the future aircraft position after a time step Δt. LPA assumes that each aircraft follows perfectly its intended trajectory during this time window. This assumption is not realistic. Indeed, many uncertainty sources can deflect an aircraft from its intended position. The uncertainty that we consider in this study, is the difference between the aircraft actual position and its intended position during the prediction time horizon Δt. This uncertainty depends on weather data accuracy, including actual wind speed and actual temperature at the aircraft flight level. These two parameters have a direct influence on the aircraft's ground speed. The uncertainty also depends on the accuracy of aircraft weight, and the initial conditions (position and velocity).

3.1. Open-loop uncertainty model

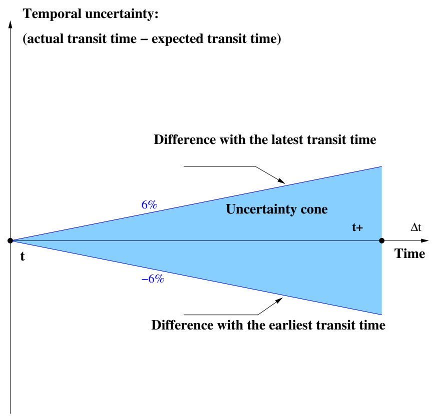

Fig. 4. Open loop uncertainty model.

The uncertainty model we use in this paper is the following. We only consider uncertainty on the longitudinal axis, that is to say along the trajectory of the aircraft. We neglect the lateral and vertical uncertainties, knowing that current Flight Management System (FMS) is able to maintain an aircraft on its intended trajectory with high precision. Therefore, the uncertainty model chosen concerns the transit time over different points of the trajectory. We consider that for 95% of the time, there is a maximal error on the wind value of ±15 Kt. In the worst case, i.e. considering the lowest possible aircraft speed (around 250 Kt), the maximal error on wind speed yields the so-called *maximal temporal error* of ±6% of the total time elapsed from the beginning of the prediction (see Figure 4).

3.2. LPA extension to uncertainties: u/LPA

Considering the above uncertainty model, we describe here how the aircraft trajectory planning problem is affected especially as regards to the aircraft protection zone (forbidden zone for other aircraft) which becomes now bigger.

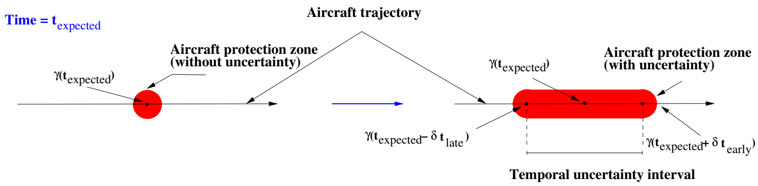

Fig. 5. Aircraft protection zone in the horizontal plane, with and without uncertainty at time $t_{expected}$.

Let $\gamma(t)$ be a 3D aircraft trajectory, with t the trajectory travelling time. For a position point $P = \gamma(t_{expected})$ where $t_{expected}$ denotes transit time expected at P, we can retrieve, from the curve in Figure 4, a temporal uncertainty interval (which we shall denote $I_{Expected}$), $[t_{expected} - \delta t_{late}, t_{expected} + \delta t_{early}]$ where δt_{late} denotes the difference with the latest transit time δt_{late} and δt_{early} is the difference with the earliest time of passage. The *new protection zone* around P is therefore no longer represented by a cylinder but by the union of the protection cylinders of all $\gamma(t)$ points, with $t \in I_{Expected}$. This new protection zone is represented in the horizontal plane in Figure 5. In the vertical plane, the protection zone is not changed.

We have now to find for every aircraft involved in a *conflict cluster* a new trajectory that connects its departure point to its arrival points while avoiding the new protection zone of any other aircraft. As the problem "*conflicts resolution*" changes, LPA must be adapted to solve this new problem. In the following, we present the various adjustments made to LPA in order to take into account uncertainty. The LPA algorithm thus adapted to uncertainties will be denoted by *u/LPA*.

3.2.1. Protection envelope

As it was the case for LPA, u/LPA will run sequentially on aircraft trajectory segments extracted from a cluster of conflict between times t and $t + \Delta t$. At the m^{th} step, the $m - 1$ constraint trajectories (protection zone) already treated are no longer represented by simple 4D tubes whose "3D section" (3D projection into the time axis) at time t is represented by a cylinder. These forbidden zones will hence forward be represented by *4D cones*, whose 3D section (at time t) is represented in Figure 5. As described above, this section at time t of the 4D cone is the union of all the protection envelopes of all possible positions of the aircraft corresponding to the temporal uncertainty interval around time t.

3.2.2. Light beam

For each aircraft sequentially considered by u/LPA, we must take into account the temporal uncertainty on its position in the wavefront propagation step. This will affect the branching procedure of the B&B implemented within u/LPA as follows.

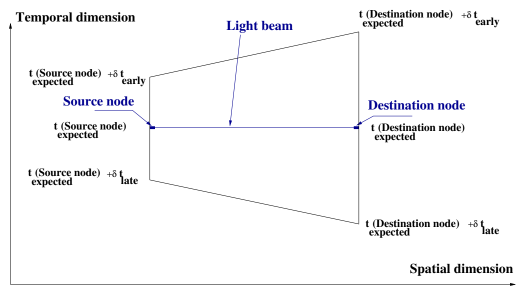

Fig. 6. Light beam adjustment to uncertainty in the u/LPA branching phase: uncertainty trapeze.

In the case without uncertainty, a node of the LPA B&B tree represented a spatial aircraft position at a given time t. In u/LPA, in order to represent the aircraft positions, at the earliest and at the latest, at time t, we must propagate *two* wavefronts around the *central wavefront* (the original wavefront, which represents the aircraft expected position): a wavefront at the earliest and a wavefront at the latest. These two wavefronts can be defined with respect to the central wavefront, by associating to each tree node representing an aircraft spatial position, a temporal uncertainty interval around time t. This uncertainty interval is extracted from the uncertainty curve (for example open loop curve Figure 4).

As in LPA, to ensure aircraft separation, our new algorithm u/LPA is defined so as to eliminate right away from the B&B search tree any light beam entering a prohibited area. In the uncertainty context: the 4D cones of the previously treated aircraft are forbiden zones. In u/LPA, a light beam connects two nodes, each of which is associated with an uncertainty interval time. Therefore, we check whether an *uncertainty trapeze* (4D space) enters a prohibited 4D cone. This trapeze (Figure 6) is defined by the initial segment (light beam without uncertainty), plus an uncertainty interval in the temporal dimension at both ends.

When considering the new trajectory model taking into account uncertainty, many more conflicts are expected to be detected. In order to reduce uncertainty and hence to reduce the problem difficulty, let us first describe the different alternatives for the future Flight Management System.

3.3. FMS

To reduce the uncertainty described above, different modes of aircraft control are being considered for future FMS. These modes are detailed in the following paragraphs.

3.3.1. *Speed control mode*

This mode does not actually reduce uncertainty. It enable to move what is commonly called *the uncertainty area* around the aircraft position (aircraft protection zone with uncertainty), in order to avoid intersecting another aircraft protection zone. This is done by controlling the aircraft speed. More specifically, aircraft will be accelerated or decelerated within the interval $[-3\%, 6\%]$ (considered acceptable in practice) of the aircraft initial velocity, during the time window horizon Δt. This mode is already available with the current FMS. However, it is the least interesting since it does not reduce the uncertainty *per se*.

3.3.2. *Final RTA mode*

This mode is also already available on the current FMS. It enable to impose the aircraft to arrive at a given point of its trajectory, at a given time called *Required Time of Arrival* (RTA) with a tolerance of ±10s. An approximate envelope curve of temporal uncertainty (that we simply call *uncertainty curve* in the sequel) with a RTA point is given in Figure 7. As before, this curve is known to be valid 95% of the time. It evolves first as the uncertainty cone of Figure 4 with a slope of ±6% of the total elapsed time from the beginning of the prediction. Then, approaching the RTA time, current FMS is designed to change the aircraft speed from the time $\frac{2}{3}$(RTA-t) (where t is the prediction starting time) so as to compensate the time error, enforcing the aircraft to be on its originally scheduled position at RTA time.

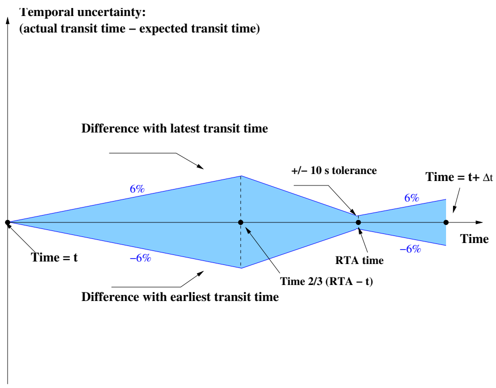

Fig. 7. Closed-loop uncertainty model with an RTA point.

This mode is currently used on final approaches. This is an improvement over the previous mode. Indeed, uncertainty is reduced in the vicinity of the RTA point. However, since the RTA is imposed at the end of the trajectory, uncertainty is only reduced in the last third of the trajectory.

3.3.3. *Multi-RTA mode*

Unlike the two previous modes, this mode is not available on current FMS. It is an extension of the final RTA mode described above: instead of imposing a single RTA point on the aircraft trajectory, we impose several RTA points throughout the aircraft trajectory. The uncertainty curve remains the same as in the previous mode: uncertainty decreases to ±10 second at each RTA point and it then increases with a slopes ±6% afterwards. Unlike the final RTA mode, the multi-RTA mode can impact conflict detection and resolution throughout the trajectory. In the sequel, we study the application of the multi-RTA mode. Our goal will be to determine the number n of RTA points to impose on each aircraft trajectory and their 4D locations (space-time) in order to find results on conflict resolution which are comparable to those obtained with LPA in the case without uncertainty.

3.3.4. *Full 4D mode*

This mode is the most demanding from the board point of view. On the one hand, it assumes as the other modes, that the aircraft follows perfectly its trajectory, and on the other hand, it requires the aircraft to pass through each point of its trajectory at the *scheduled time*. Here, one finds the problem modeling made in [1] (without any temporal uncertainty on the aircraft position), and LPA can be used then.

4. Global methodology

In this section we describe the overall methodology to address the problem of conflict resolution under uncertainty. First, in view of the FMS multi-RTA mode, we introduce the new "*conflict resolution with RTA*" problem arisen. Then, we present the different resolution steps.

4.1. Problem statement

When considering the FMS multi-RTA mode, the "conflict resolution under uncertainty" problem can be divided into two sub-problems: the first one is to place RTA points on aircraft trajectories and the second one is to generate conflict-free trajectories based on the closed loop uncertainty curve which is completely defined once the RTA points are placed.

The decision variables of the first sub-problem are: the number n_i of RTA points we must place on each aircraft a_i involved in a conflict cluster, times t_{ij} and spatial positions p_{ij}, $j \in \{1..n_i\}$ of the RTA points. The unknowns of the second sub-problem are the trajectories $\gamma_i(t)$ of each aircraft a_i. In the sequel, we address the "conflict resolution under uncertainty" problem, first without imposing RTA points then using them.

4.2. Phase 1: open loop uncertainty

In this first step, to take into account a realistic air traffic situation, we consider the uncertainty on aircraft position based on an open loop uncertainty model, that is to say without imposing RTA points. In order to solve conflict, u/LPA is called with an open loop uncertainty curve (this curve is used to determine the other aircraft protection zones (3.2.1) and the light beam in the B&B process (3.2.2)). If u/LPA fails to produce for every aircraft involved in a conflict cluster a new conflict free trajectory, we pass to the second phase.

4.3. Phase 2: the use of RTA points

In this second phase, we impose RTA points. Therefore, by reducing uncertainty, residual conflicts may be solved (those not resolved by the first phase). As mentioned above, the number and the way (when/where) these RTA points are placed on a given trajectory is an unknown of the problem, we must determine.

To implement the second phase of u/LPA, we must find the (space-time) positions of RTA points, that u/LPA will impose to aircraft in order to generate conflict-free trajectories. Recall that an RTA point must match, a time (a point on the time axis), and a spatial point belonging to the (solution) trajectory generated by u/LPA. Therefore we have to force an aircraft to be at a given location (called *spatial RTA*), at a specific time (called *temporal RTA*). However, imposing a spatial RTA implies that one knows in advance at least one point of the solution trajectory that avoids conflicts. However, we can not determine in advance (before resolution) the space area where the solution trajectory will be found.

To work around this problem, we propose only impose a temporal RTA regardless, for now, to the position (spatial RTA). In other words, we choose an RTA time in the vicinity of which the uncertainty in the time dimension will be (by construction) reduced. The corresponding spatial position will be determined a posteriori, once u/LPA generates a solution trajectory. That is to say, that during trajectory construction by u/LPA and especially during the branching process of B&B, uncertainty trapeze described above will have bases (temporal dimension) that match the closed loop uncertainty curve. This uncertainty curve is completely determined by the temporal RTA imposed on the trajectory under construction. Similarly, the protection envelopes (4D cones) of constraint trajectories already processed by u/LPA are determined by closed loop uncertainty curves (these curves are completely defined by the temporal RTA imposed to each one of these trajectories).

It remains now to specify how to determine an optimal temporal RTA that has to be imposed on a particular aircraft of the cluster, so that ultimately generate trajectories without conflict. Intuitively, we suspect that to generate conflict-free trajectories, we must reduce uncertainty on time intervals where aircraft are the closest. Indeed, the first difficulty of conflict resolution problem comes from the spatial proximity of aircraft, to which is then added temporal uncertainty. Therefore, we propose to use this following heuristic in placing temporal RTA: imposing on all conflicting aircraft (unresolved in u/LPA first phase), a temporal RTA corresponding to the time where, before resolution and considering an open loop uncertainty, each of them was in conflict with another aircraft. Indeed, this point belongs to the time interval where, before resolution, aircraft came closest.

Once we have placed temporal RTA, we call u/LPA with the closed loop curve in order to generate conflict-free trajectories. The spatial RTA p_{ij} for each aircraft a_i are then the points of the new trajectory γ_i corresponding to the temporal RTA t_{ij}. In order to determine the total number n_i of RTA points to impose on a given trajectory, we took as an agreement to place one RTA point by time window when necessary (when phase 1 of resolution fail).

Now we have described our methodology, we will present, in the next section, numerical results obtained when we apply our methodology on a real conflict resolution problem taking into account uncertainty models above described.

5. Numerical results

We now detail results given by our methodology on the same day of traffic over France tested in [1], this time taking into account uncertainty on aircraft positions. For this, we use the same process as the one used in [1], with the same parameter values for u/LPA and the same computer setting. More precisely, we set the sampling angle $d\theta$ to $\frac{\Pi}{36}$, the time step dt to 15 seconds, the weighting coefficient α to 0.9 and the maximum index I_{max} to 2. The experiment was performed on a 2.33 GHz machine running under the Ubuntu Linux operating system with 1024 MB of RAM. u/LPA and the global methodology is programmed in java.

First, we detail phase 1 of our methodology (case without RTA points). Then, we apply phase 2 of our methodology, where we use RTA to resolve remaining conflicts. Finally, we end up with a result analysis.

5.1. Phase 1: open-loop uncertainty

We apply the first phase of u/LPA, that is to say we consider the open loop uncertainty model. We present here results obtained for the half-day traffic of August 12, 2008 from midnight to noon. On one day, there is two maxima of traffic: at 8 am and at 6 pm. Treating half a day from midnight to noon is therefore representative of the different traffic situations on the whole day.

The initial trajectories (before conflict resolution) induced 2688 conflict clusters, each of which involving from 2 to 18 aircraft. For the same half day, LPA (without taking into account uncertainty) found only 1611 conflict clusters. The increased number of conflicts detected is consistent with our expectations.

LPA previously solved nearly every conflict, with only 11 clusters for which it did not generate for every aircraft an alternative conflict-free trajectory (case were aircraft are already in conflict at the beginning of the simulation). When considering uncertainty, there are now 307 conflict clusters that u/LPA cannot solve, i.e. 88% of conflicts are solved, 1805 trajectories were modified. Recall that only 1349 trajectories were modified when uncertainty was not taken into account. This confirms the difficulty of this new framework taking into account uncertainty. The overall computation time is approximately 12 hours, against 9 hours without uncertainties for the same half-day of traffic.

As u/LPA with the open-loop uncertainty model only managed to solve 88% of the conflicts, in the next section we apply the second phase of u/LPA: using RTA points.

5.2. Phase 2: imposing RTA points

In this section, we place the temporal RTA at moments when trajectories of two or more aircraft were in conflict before resolution. We treat here the same half day of traffic from midnight to noon.

The initial trajectories (before conflict resolution) lead here, 3174 conflict clusters, each of which involving 2 to 16 aircraft. This gives a higher number of clusters than the one obtained in the case without RTA. This can be explained as follows. When we only applied phase 1 of our methodology, clusters for which we did not find solutions, were recorded as unresolved, but aircraft trajectories involved in these clusters have not been modified. With the implementation of RTA points, some clusters have been resolved and the aircraft trajectories involved have been changed in the current time window, but may have induced conflicts on subsequent time windows.

As expected, by reducing uncertainty through RTA points, the number of unresolved conflict clusters decreases. Now, only 210 clusters remains unresolved, which increases the resolution percentage to 93%. To obtain such a result, 2116 trajectories were modified by only applying RTA points (only aircraft that have been treated first by u/LPA, in resolution sequential order, keep their original trajectories but can be imposed an RTA point), by only imposing changes in direction (for aircraft involved in a cluster that has been resolved by phase 1 of our methodology), or by both. Thus, 697 RTA points have been imposed on the treated trajectory set, with a maximum of 5 RTA points per trajectory. The overall computation time is approximately 14 hours (for the half-day of traffic).

5.3. Result analysis

Taking into account a more realistic traffic than the one considered in [1], that is to say taking into account uncertainty on aircraft positions, there has been a considerable increase in the problem difficulty. Indeed, the number of detected conflicts is 1.5 times greater than in the case without uncertainty, due to the protection-area volume growth, for the same traffic situation. On the other hand, the conflict resolution percentage drops to 88% in the case of open-loop uncertainty, and improves to 93% when applying RTA points. Unfortunately, this result remains below the results obtained in subsection Real-world problem. Two reasons may explain this mitigated result. First, the situations for which u/LPA failed to find a solution are very difficult to solve, and in this case, we should apply a full 4D control type process to the involved trajectories, at least during the time window without solution. The second comes from the way we have placed the temporal RTA. Indeed, we proposed an intuitive rule for RTA placement, but there are probably more sensible rules that would achieve results that could be almost as good as the ones obtained in the framework without uncertainty. Future work could involve experimenting such rules.

6. Conclusion and perspectives

In this paper, we adapted the Light Propagation Algorithm introduced in [1] to deal with longitudinal uncertainty on aircraft positions. We developed a methodology that permits to solve real-world conflict resolution problems under uncertainty. This methodology includes two steps. The first step takes into account the conservative open-loop uncertainty model whereas the second step imposes RTA points on some conflicting trajectories. We obtain encouraging results on historical data from a half day of traffic (4000 flights) over the French airspace. Future work will involve improvement of the way we place RTA.

Acknowledgements

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